Multi-Energy X-Ray Diagnostic for W transport studies in the WEST tokamak

O. Chellaï[1], L. F. Delgado-Aparicio[1], D. Vezinet [2], T. Barbui[1], K. W. Hill[1], N. Pablant[1], B. Stratton[1], P. Malard[2], P. Van Meter[3,4]

[1]*Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*
[2]*IRFM CEA Cadarache, Saint Paul lez Durance, France*
[3]*Department of Engineering Physics, University of Wisconsin-Madison, Madison, WI, USA*
[4]*Department of Radiology, Mayo Clinic, Rochester, MN, USA*

Abstract

A compact multi-energy ($\sim 1.6-30$ keV) soft x-ray diagnostic (ME-SXR) was designed for impurity transport studies and electron-temperature measurements in the WEST tokamak. The design, installation and capabilities of the diagnostic are presented here. In parallel, a versatile synthetic diagnostic (SD) is under development. The SD is based on the FLYCHK suite [1] which computes the charge state distribution and x-ray emissivity of a selected impurity. The SD is presented here and applied to two WEST dicharges.

Motivations

In future fusion reactors, high-Z materials are seen as the best candidates for plasma facing components (PCFs) because of their resilience to high heat-flux with low erosion rates, low tritium retention and lower nuclear damage activation associated with neutron fluxes. Their presence in the plasma, however, is known to restrict the operational space of tokamaks since it induces significant radiation losses in the plasma core associated with radiative collapses or disruptions. It is therefore necessary to :

- understand the sources, transport/confinement of high-Z impurities;
- control high-Z impurity transport to avoid accumulation in the core, which is needed to achieve and maintain high fusion performance;
- provide a diagnostic that should become, in the near future, an essential part of a control algorithm coupled to physics & engineer actuators for minimizing impurity accumulation in tokamaks.

For these purposes, a novel multi-energy soft x-ray (ME-SXR) diagnostic has been built by the Princeton Plasma Physics Laboratory and is being deployed in WEST (W Environment in Steady-state Tokamak), Cadarache, France. The WEST device is an ideal environment to study the transport of high-Z impurities, designed to test the ITER-like tungsten plasma facing components in a long pulse ($\sim$1000 s) scenario.

The MESXR diagnostic design

The ME-SXR was designed as a pinhole-viewing camera. The camera has a 2D, pixelated, array detector, the PILATUS 3 X 100K-M Si, based on a Si lattice and manufactured by DECTRIS Ltd which is sensitive to soft x-rays in the range 1.6-30 keV. The detector is made of 487 x 195 $\approx$ 100k pixels of dimension 172 μm x 172 μm, covering an active area of 33.5 mm $\times$ 83.8 mm. The detector is mounted on a cylindrical casing put at a 5-10 mTorr vacuum to enable working in a low-humidity environment, necessary to its operation, and to limit the absorption of the soft x-ray. The window sealing the WEST vacuum is made of berilyum and has a thickness of 300 μm, providing simultaneously attenuation on the bright W lines below 6 keV and a protection to the WEST vacuum.

The novelty provided by the detector is the capability of setting independently the lower energy threshold E_c for each one of the $\approx$ 100k pixels providing a flexibility on the energy-setting configurations . A discussion on the different energy configurations and their use is available in [2]. A calibration effort performed in [3] enables the use of the ME-SXR over three energy ranges: low (2.3-6 keV), medium (4.5-13.5 keV) and high (5.4-21 keV). The three energy ranges have an energy resolution of 330, 640 and 950 eV, respectively, enabling the probing of either the W lines or the bremsstrahlung continuum. The targeted spatial resolution is between 1.4 and 2.1 cm and the temporal resultion is 2 ms.

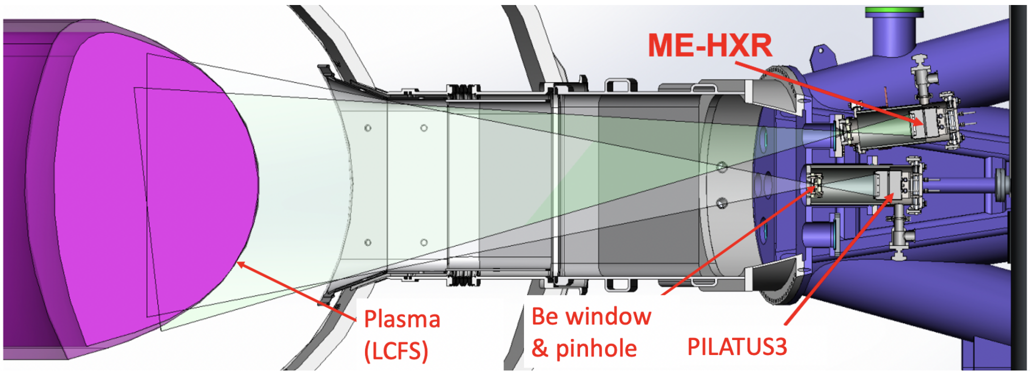

Figure 1: ME-SXR & ME-HXR integration on the WEST tokamak.

The synthetic diagnostic

A synthetic diagnostic was implemented to model the plasma soft x-ray emission and the response of the ME-SXR diagnostic given any artbitrary impurity mix in the plasma. A large database of soft x-ray emissivity spectra $\mathscr{F}(n_e, T_e, E)$ –taking into account bremsstrahlung, recombination and line emission– and average charge state $\langle Z \rangle_{\mathscr{F}_i}(T_e)$ was computed for the following elements using the FLYCHK code [1]: Al, Ar, B, Be, C, Ca, Fe, H, He, Mo, N, Ni, O, Si, W, Xe. Fig. 2 show example of those spectra $\mathscr{F}$ for C, O and W, obtained for $n_i = 10^{20} m^{-3}$ and for several values of T_e ranging between 0.5 and 6 keV. In general, we can see that the emissivity increases with T_e. In Fig. 2(a) and (b), we see that C and O do not have associated line emission in the considered photon energy range (2-30 keV), and the linear shape of the spectra in the logarithmic scale is due to the bremsstrahlung emission. On the opposite, we can see in Fig. 2(c) that strong line emission is associated with W in the region of the spectrum < 13 keV which, depending on T_e, can be several order of magnitudes larger than bremsstrahlung and recombination radiation.

The number of photon counts ε_i emitted by a voume element by the species i that can be measured by the ME-SXR is given by

$$\varepsilon_i = \int_{E_0}^{E_1} \frac{\mathscr{F}_i(n_{e,i}, T_e, E)}{E} \tau_{Be} \tau_V \mathscr{A}_{Si} \mathscr{S}_{Det}(E_c, E) dE, \qquad (1)$$

where E is the photon energy, E_c the threshold energy set on the detector and $\tau_{Be} \tau_V \mathscr{A}_{Si} \mathscr{S}_{Det}(E_c, E)$ the energy response of the ME-SXR diagnostic accounting for the transmission of the Be window and the vaccum, the absorption of the silicon lattice and the energy response of each pixel.

The total number of photon count is obtained by summing the contribution of each ion species

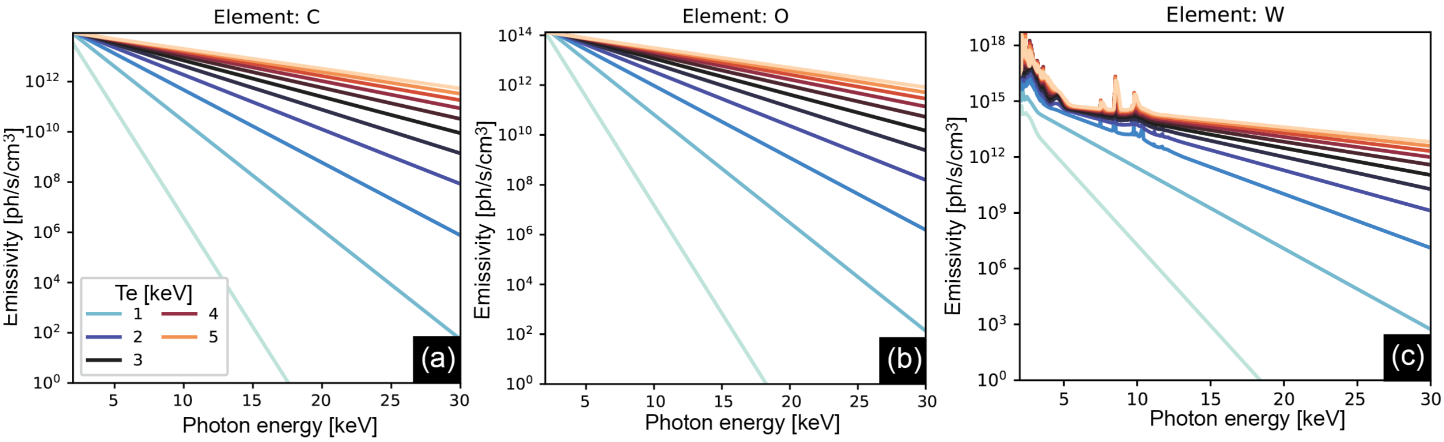

Figure 2: Emissivity spectrum from O, C and W

$$\varepsilon(E_c,R,Z) = \sum_i^n \varepsilon_i(E_c,R,Z), \tag{2}$$

and the deuterium concentration is obtained from the quasi-neutrality equation

$$\frac{n_D}{n_e} = 1 - \sum_i^n \frac{n_{Z_i}}{n_e} \cdot \langle Z \rangle_{\mathscr{F}_i}(T_e). \tag{3}$$

$\varepsilon(E_c,R,Z)$ is then integrated along the line of sight using the ToFu code [4] to obtain the soft x-ray brightness B. The number of photon counts N_{ph} per unit of time impinging on each individual pixel is linked to B by

$$\Delta N_{ph}/\Delta t = \eta(\theta) B \tag{4}$$

where $\eta(\theta)$ is the étendue computed as $\eta(\theta) = \frac{A_{pin}A_{pix}}{4\pi d^2 \cos^4(\theta)}$, A_{pin} and A_{pix} being respectively the pinhole and the pixel area, d he distance from the detector to the pinhole, and θ the angle between the pixel's viewing chord and the vector normal to the pinhole.

Soft x-ray emission from two WEST discharges

Two WEST discharges are studied below. The first discharge # 56915 is an ohmic-heated lower single null plasma with $n_e \approx 6 \times 10^{19}\,\mathrm{m}^{-3}$ and $T_e \approx 0.9$keV. The second discharge # 54178 is an upper single null plasma with $n_e \approx 4 \times 10^{19}\,\mathrm{m}^{-3}$ and $T_e \approx 5.5$keV.In the following, we will refer to # 59615 and 54178 as the low- and high-Te plasma, respectively. We consider the following impurity mix of C, O and W homothetic to the electron density: $n_C/n_e = 2 \times 10^{-2}$, $n_O/n_e = 2 \times 10^{-2}$ and $n_W/n_e = 5 \times 10^{-4}$.

The number of photon counts $N_{ph,j}$ on each pixel j is computed for each case using the synthetic diagnostic described above. $N_{ph,j}$ summed on the pixels located on the same pixel row, along the toroidal direction. The results are shown in Fig. 3(a) and (b) for # 56915 and # 54178, respectively. The results are obtained for several values of energy threshold E_c, and therefore several responses $\mathscr{S}_{Det}(E_c,E)$ in the medium energy range of the detector. In both cases, the photon counts peaks for the chords viewing the center of the plasma and goes down to zero at the edges of the detector (index of the pixel row: 0 and 486), which will later be necessary to enable spatial inversion of the ME-SXR signals. The increase in T_e between the two discharges is responsible for an order of magnitude increase in the photon counts ($\sim \times 10$ for $E_c = 4.5$ keV). As discussed in the previous section, this is mainly

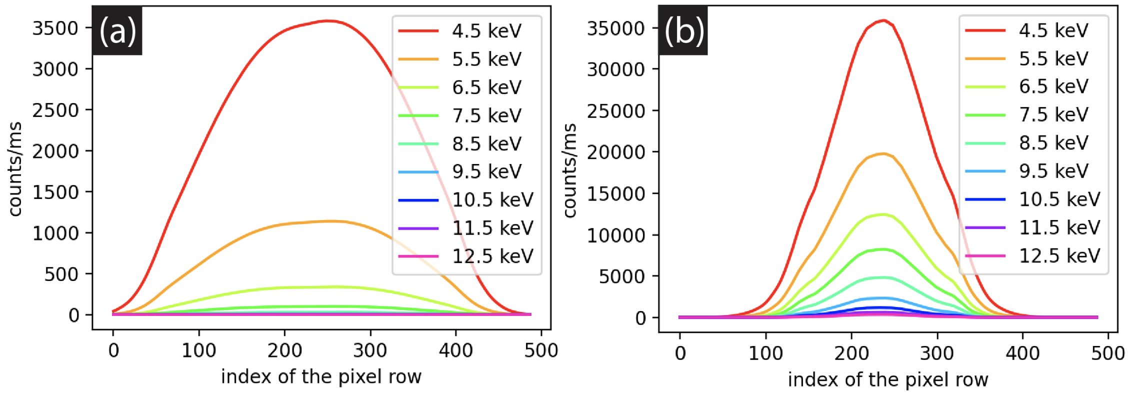

Figure 3: (a) and (b): Chord brightnesses summed on the pixels rows along the toroidal direction for # 56915 and # 54178, respectively, for several values of energy threshold E_c in the medium energy range of the detector.

caused by increased W line emission and Bremsstrahlung contribution from C, O and W to the plasma emissivity associated with the increase in T_e. In particular, the variation in the ratio between the photon counts/ms obtained for $E_c = 4.5\,\text{keV}$ and $E_c = 5.5\,\text{keV}$ (1/3 and 1/2, respectively) between the two cases is due to the strong increase of the intensity of the W line emission with T_e.

The new synthetic diagnostic will be compared to experimental data from WEST discharges in the C6 campaign which is planned for early 2022. Its implementation for other machines (TCV, NSTX-U and ITER) is ongoing and will be subject to a separate publication.

Acknowledgment

This work is supported by the U.S. DOE-OFES under Contract No. as DOE contract DE-AC02-09CH11466

References

[1] H-K Chung, MH Chen, WL Morgan, Yu Ralchenko, and RW Lee. Flychk: Generalized population kinetics and spectral model for rapid spectroscopic analysis for all elements. *High energy density physics*, 1(1):3–12, 2005.

[2] P.D. VanMeter, L.F. Delgado-Aparicio, L.M. Reusch, and D.J. Den Hartog. A versatile multi-energy soft x-ray diagnostic for te measurements in the madison symmetric torus. *Journal of Instrumentation*, 14(09):C09009–C09009, sep 2019.

[3] O Chellai, LF Delgado-Aparicio, P VanMeter, T Barbui, J Wallace, KW Hill, N Pablant, B Stratton, C Disch, B Luethi, et al. Calibration of a versatile multi-energy soft x-ray diagnostic for west long pulse plasmas. *Review of Scientific Instruments*, 92(4):043509, 2021.

[4] D Vezinet, V Igochine, M Weiland, Q Yu, A Gude, D Meshcheriakov, M Sertoli, EUROfusion MST1 Team, et al. Non-monotonic growth rates of sawtooth precursors evidenced with a new method on asdex upgrade. *Nuclear Fusion*, 56(8):086001, 2016.